A socio-mathematical approach to exploring conflicts between energy retrofit and perceived heritage character

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A B S T R A C T

Improving the energy efficiency of buildings is a key climate change mitigation strategy. The application of which will require substantial improvements in the pre-existing stock; a subset of which are buildings of historic importance. Retrofitting such buildings is controversial, as historic elements might be altered or covered up, thereby changing the character of the building. In this work, we introduce a novel socio-mathematical method to aid the resolution of this controversy. Firstly, we garner in a new way the views of 116 members of the public about the acceptability of 15 common retrofit measures. Secondly, the public's ranking of the acceptability of the measures with respect to heritage impact is compared to a ranking of the energy saving given by the measures when analysed using a dynamic thermal simulation of the building. No simple correlation is found; hence it is concluded that measures that present greater energy savings are not de facto more intrusive, and that there is the potential for a constructive dialogue between those inspired by a conservation agenda and those targeting carbon savings. Finally, by using a Pareto front approach, a new theory is developed of how to identify measures that are sensible in the eyes of both parties. This new three-stage process will be of use to those in Government attempting to resolve such conflicts or set national guidance.

1. Introduction

Buildings consume about 40% of the energy and emit 36% of the anthropogenic greenhouse gas emissions in Europe [1], and many countries have ambitious targets to reduce these emissions [2]. These targets are challenging for new buildings and even more so for the pre-existing stock. In the UK for example, 20% of dwellings were built before 1919 and a further 20% between 1920 and 1939 [3]. In addition, there are many World Heritage cities, such as Bath (UK), Graz (Austria), Trogir (Croatia), Verona (Italy), Valletta (Malta), Safranbolu (Turkey), Cuzco (Peru) and, Quito (Ecuador) where large areas are considered historically highly sensitive.

Alongside the conservation agenda, there is also the need to ensure suitable environmental conditions in these older properties, particularly wintertime temperatures. The average temperature homes are heated to in the UK has risen from 13 °C in 1970 to 18 °C by 2000 and is continuing to rise, as is the number of rooms heated [4]. Providing such temperatures through traditional heating systems in properties with poorly performing envelopes, places further pressure on carbon targets.

Unfortunately, retrofitting measures, such as insulating building surfaces, replacing windows or adding PV panels, have the potential to change the identity and contexts of the building, particularly those in historically sensitive areas. Hence there is the need to find a balance between reducing greenhouse gas emissions and heritage value. In practice, this will be difficult [5].

In finding this balance it has been common to elicit the opinions of experts in the retrofit and historic fields, rather than those of the public, which are largely unknown and understudied. This work adopts a new approach by bringing the public into the debate and eliciting their views in a novel way. When discussing the impact of alterations with a non-professional audience, there is clearly the need to add context. In this work this is achieved by using a real building and showing participants photos of the measures that might be used to save energy, then asking them to rank the measures on a 5-point scale from acceptable to unacceptable. A dynamic thermal model of the building is then constructed, the same measures applied and ranked in terms of energy savings. These two rankings are then compared to discover if there is any relationship (positive or negative) between the amount of energy a measure can save and the public acceptability of the measure. Finally, the concept of Pareto optimality [6] is used to further analyse the situation and to generate a new socio-mathematical methodology for rationally helping to resolve conflicts between conservation-minded and efficiency-minded teams when discussing retrofit.

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1.1. Previous work

Energy conservation in historic buildings has been studied from various viewpoints. Work, like that of Forster et al. [7], focuses on the environmental impacts of specific conservation methods, for instance, environmentally friendly repair techniques for masonry. Likewise, Zagorskas et al. [8] sought a solution for excessive moisture in brick walls through comparisons of the performance of different insulation materials. Other studies have concentrated on energy savings. Cluver and Randall [9] carried out a life cycle analysis to examine potential energy saving measures. Ascione et al. [10] have suggested a multidisciplinary approach is needed when discussing retrofitting in order to include all components: energy efficiency, occupants, cost, health and comfort. Tupenaite [11] developed a four-step plan, from collecting data to delivering the final design for a renovation project. Whereas, Ma et al. [12] started with a pre-retrofitting survey and progressed through to energy saving estimations of different scenarios. Although these two studies are related to existing buildings in general, rather than specifically historic buildings, they give an idea of the importance of using an individual building-specific approach to retrofit, which includes a pre-design stage. This is the approach adopted in this paper.

In a comprehensive study of 246 members of the public, Anderson and Robinson [13] assessed public attitudes towards different energy efficiency measures. Unfortunately, the study does not present the survey structure used, stating instead that participants evaluated the "options for improving local policy on listed buildings". The potential energy savings from these measures were not discussed. In general, people found alterations that had direct visual impact on the building's character, such as external wall insulation and double glazing, to be inappropriate for historic buildings.

Broström et al. [14] assessed different energy efficient scenarios in the case of a historic building in Sweden. They compared each scenario, in terms of their energy and cost saving capabilities, and discussed the possible visual and material effects of the components of the scenarios. As a result, they found that the EU's 20% energy reduction target [15] could be achieved without overly conflicting the historic building's character. However, it was also underlined that more ambitious energy saving targets would require more radical changes to historic buildings, for example insulating the exterior walls. Public opinion was not specifically integrated into the process, but at the end of the energy and cost optimization analysis, an iterative procedure was suggested, with the participation of users and building owners to find the best solution.

Héberlé and Burgholzer [16] examined seven typical Alsatian historic buildings to try and find the balance between energy efficiency, comfort and heritage. Three different energy retrofit scenarios were produced: 1. high energy efficiency with eco-materials, 2. a balance between energy efficiency and heritage conservation, 3. high heritage conservation. Finally, these scenarios were evaluated by experts for: energy saving, thermal comfort in summer, thermal comfort in winter, moisture damage and heritage conservation. They found the scenario with high energy efficiency with eco-materials had the most negative impact on the heritage value of the buildings, whereas the least energy saving scenario had the least effect. Şahin et al. [17] also looked at three retrofitting options based on their energy saving capacity. The researchers then examined whether the options are compatible with historic building character. They concluded that minor energy savings can be achieved with minimal loss of architectural and historical value.

Ascione et al. [1] used a dynamic energy simulation, together with an assessment of a building's historic value to look at various options for energy saving retrofits to find an acceptable solution that offered a 38% reduction in greenhouse gas emissions.

Roberti et al. [18] attempted to find a balance between energy efficiency and historic value by attempting to place historic value on a numeric scale based on the judgement of experts then applying a multi-criteria optimization. They gathered both historic compatibility and energy efficiency scores of the retrofitting alterations, and discussed the balance of these scores. They concluded that a 73% decrease in energy demand could be achieved by accepting an 11% decrease in conservation compatibility.

1.2. Conservation guidance

Historic buildings are valuable because of the special significance they possess. To preserve this significance, alterations are governed by conservation principles, often those determined by the International Council on Monuments and Sites (ICOMOS) and the United Nations Educational, Scientific and Cultural Organization [19]. The Burra Charter provides international conservation guidance [20,21] and states, "change may be necessary to retain cultural significance, but is undesirable where it reduces cultural significance" [22], pg. 6]. Energy retrofitting can require both minor and major changes to a building, and Ascione et al. [1], pg. 173] claim that many of these changes are questionable in terms of their compatibility with a historic building's character and their acceptability depends on "how much of the substance of the historic building will be lost, and in which way the refurbishment will interfere with the image of the architecture". Again, according to Godwin [23], energy retrofit alterations should secure the architectural and historic significance of the building so as not to harm the building's character.

Historic buildings are not ordinary buildings. They have special national and worldwide significance. These significances are specified by Historic England [24] as evidential, historic, aesthetic and communal and any alterations that have the potential to undermine these can cause a loss of value. Energy retrofit measures are also alterations and need listed building consent. As stated by the Planning (Listed Buildings and Conservation Areas) Act 1990 [25] and the National Planning Policy Framework (NPPF) [26], local authorities are responsible for giving this consent. As the study building is in Bath, it is subject to the policies covered by the Bath and North East Somerset (B&NES) Local Plan [27] which draws a general perspective for the alteration of historic buildings by stating that improvements can be applied to listed buildings, provided that there will be no change in building character and no decrease in architectural and historical interests. Under the current framework several of the retrofit measures included in this work would not be allowed for this particular building. The reason we included them was to gauge to public's view of them. If only measures that would be allowed were included, the study would have been biased and reinforced the current expert-led situation, rather than pointing to the views that might be gathered if the public was part of the process.

1.3. Public engagement

The determination of the acceptability of an alteration often depends on a single person, for example an expert in architectural history or heritage [28,29]. The lack of public input into the process possibly comes from errors in the past, where public involvement and lack of expert control may have led to the destruction of historic identity, for example, pragmatic and careless restoration in the Victorian Period [30,31], or, after World War II, and up to the 1980's, where existing buildings, including historic buildings, were adapted along largely economic lines, rather than under a conservation philosophy [32]. According to Pendlebury [33], this tension between retrofit and conservation is still there. However, this is an age of paradigm shifts in conservation, with a desire to open the process up to the whole of society [34], and to ensure buildings meet the cultural, economic, social and environmental needs of the public. And indeed, while historic buildings increase social and cultural values by their existence, the cultural importance of heritage is nourished through the value given by the public to it [14]. Hence, there is a growing desire to welcome the public into the debate [35].

Unfortunately, at present the retrofitting process is still delivered by

experts and bypasses the public [36], and according to de Groot et al. [37], their views will not be accurately represented by experts, possibly leading to the relationship between public and heritage being undermined. When this happens, it has been suggested that the existential value that historic buildings offer to people, namely, identity, sense of community, and attachment, disappears [38].

2. Method

Members of the public were asked to rank the impact of fifteen retrofit measures on the historic nature of a building. This is achieved by showing participants photographs of the building and of the same measures applied to other buildings, thereby ensuring they have an understanding of the context and the potential visual impact of the measures. The public's ranking is then compared with the ranking of the energy savings given by the fifteen measures within a dynamic thermal model of the building. From the correlation of the two rankings, tensions and opportunities are identified, and by plotting the Pareto front, solutions that are rational, in that they are non-dominated, and are acceptable in terms of both public perception and energy savings were identified. This method has been designed to be simple to apply to ensure it is of practical utility.

2.1. The study building

The Herschel Museum of Astronomy, a grade II* listed building, was built as a private house around 1764–1770, as part of the terraced houses of New King Street, Bath UK (Fig. 1). Not only is the building of architectural significance, it hosted the astronomer William Herschel from 1777 to 1784, where he discovered Uranus from the courtyard [39]. Between 1981 and 2000, it saw major alterations, including the reconstruction of part of the rear elevation and garden walls and the reapplication of wallpaper, in order to obtain the authentic appearance and structural soundness of the original building [40,41].

The building is a typical middle-grade Georgian terraced house with a basement kitchen, ground floor dining room, and first floor drawing room [42] (together with the second and attic floors, the house is five storeys in total). The primary building materials are Bath stone ashlar, at the front, and coursed rubble at the rear. Unlike the windows on the front elevation, the windows at the rear extend to the floor, which is commonly observed in houses built after the 18th century. Therefore, there is a strong likelihood that the original windows were replaced. The double mansard slate roof is another important characteristic of the house, as it can be easily seen from the street and garden.

The interior is partly furnished (Fig. 2). Besides the movable furniture, there are built-in cabinets in the south-facing rooms to exhibit items related to astronomy. The wallpaper and the carpets are new but their production techniques and textures were based on those used in other Georgian buildings in Bath, specifically the Beckford's Tower [40].

It should be understood that it is not being suggested that the list of retrofit measures being studied would be used, or could even legally be used, on the Herschel Museum, or a similarly important building. The building itself is simply being used to demonstrate the approach.

2.2. The survey

The survey consisted of three sections. The first was a short description about the aim and scope of the research. The second introduced the building, via text and photographs. The third section asked the participants to rank the acceptability of the 15 possible retrofit alterations within a 5-point Likert-scale (1 being the least acceptable and 5, the most acceptable). The alterations mentioned came from guidance given in, Energy Efficiency and Historic Buildings [3], Sustainable and Retrofitting Supplementary Planning Documents [43] and Energy Efficiency & Renewable Energy Guidance for Listed Buildings

and Undesignated Historic Buildings [44]. A novel element of this work is that, rather than relying only on the pre-existing knowledge of the measures participants might have, descriptive photographs depicting the application of each retrofit measure were included to help the participant to imagine the impact of the alterations (Fig. 3).

After constructing the survey, a pilot study was completed with six participants to check whether the survey was functional. From this, it was found that the terms "draught proofing" and "photovoltaic panels" were overly technical and the survey adjusted to provide additional information on these measures. The final survey was complete by 116 participants from 20th July 2017 to 5th August 2017 Recruitment was via e-mail and Facebook groups to Bath residents (31 participants) and asking people in the city centre at random (85 participants).

2.3. Energy analysis

A dynamic simulation of the building was constructed in IES (Integrated Environmental Solutions) Virtual Environment 2017. IES is a dynamic thermal modelling software package that has been validated against a number of Regional, National and International standards, including CIBSE and ASHRAE[1] The software uses representative weather for a given location on an hourly timescale to simulate internal temperatures and energy use over an entire year, based upon user inputs of efficiencies, gains and profiles of occupancy and energy use. Plans of the building [46] together with a survey by the authors was used to define the geometry and constructions. The garden extension at basement level, erected in 2011, was excluded from both the public survey and the dynamic simulation. (See Appendix for the building data.) The following retrofit measures were considered (see Appendix for more details): 1. Draught proofing of the floor boards; 2. Draught proofing of windows and doors; 3. Replacing windows with double-glazed replicas; 4. Use of thick insulated curtains for doors and windows; 5. Installing secondary glazing; 6. Installing photovoltaic slates on the roof facing the street; 7. Installing wood burners in fireplaces; 8. Installing a ventilation terminal on the ceiling (of itself this would not save energy, but would if part of a mechanical ventilation with a heat recovery (MVHR) system, and sufficient airtightness could be provided); 9. Installing solar photovoltaic panels on the street-facing roof; 10. Installing external window shutters; 11. Applying internal wall insulation; 12. Installing a solar hot water panel on the street-facing roof; 13. Installing modern radiators and a gas boiler; 14. Replacing floors with new insulated flooring; 15. Applying external wall insulation.

The measures chosen could have been achieved in a variety of ways, for example various different insulation products from different manufacturers. Although our list of measures was formed from a careful consideration of what would form a wide set of possibilities, our precise choice of manufacturer and materials (for example which manufacture's ventilation terminal to use) was based on those we had photographs for.

3. Results

3.1. Survey results

The responses on the 5-point scale were grouped into 3 categories: unacceptable (1 and 2), neither unacceptable nor acceptable (neutral) (3), and acceptable (4 and 5). The percentage, p, of people in each of these groups (Table 1) for each alteration presented in the survey became the determinant for which alterations were considered acceptable:

If $p(\text{acceptable}) > p(\text{neutral})$ and $p(\text{acceptable}) > p(\text{unacceptable})$ then alteration = acceptable

Else alteration = unacceptable (1)

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[1] The full list can be found at https://www.iesve.com/software/software-validation.

Fig. 1. Left, the front elevation, and right, general view of the street (by authors).

Fig. 2. Interior views (by authors).

As a result, draught proofing of windows, doors, and floor, photo-voltaic (PV) slates on the roof, insulated curtains for openings, double and secondary glazing, wood burners in the fireplaces, and ventilation terminals, were found to be acceptable. The remaining alterations (replacement of floors, insulation of the façades, modern radiators, solar and PV panels, and external shutters) were deemed unacceptable.

As Table 1 shows, draught proofing was regarded as the most acceptable solution. This matches with common guidance, for example, Historic England's [3] statement that air infiltration and draught proofing should be the first step in retrofit projects, and Héberlé, & Burgholzer [16], who suggest that it has minimum visual impact. Except for double glazing, the results for openings are as expected, since both secondary glazing and insulated curtains are simple additions not requiring the replacement of any existing building elements. That the replacement of historic windows with double glazing was seen as acceptable might seem surprising, as it is opposed to the principles of authenticity and reversibility. However, previous studies also found the same result. Anderson & Robinson [13] found that 71% of the Bath residents who participated in their research stood for a permissive policy regarding the use of double glazed windows in listed buildings. Again, Sunikka-Blank and Galvin [29] observed that homeowners in Cambridge appreciated the sense of nostalgia but they are not always interested in whether this was achieved by replica or preservation. These results highlight the potential for difference between expert and public opinion.

In general, respondents found PV slates to be compatible with building character, but solar thermal hot water or PV panels on the roof were regarded as incompatible. Again, wood burners in existing fireplaces were acceptable but modern radiators considered to be highly unacceptable. The replacement of the floor with new insulated flooring and exterior wall insulation clearly compromise the history of the building and were deemed the most unacceptable.

Fig. 3. An example (secondary glazing) of the photographs of the measures shown to the participants [45].

Table 1
Survey ranking (measures deemed acceptable under equation (1) are highlighted in orange and unacceptable measures in blue).

Acceptable alterations ranked most to least acceptable	Number and percentages of people choosing acceptability categories		
	Acceptable	Neutral	Unacceptable
1. Draught proofing of ground floor	90 (77.6%)	15(12.90%)	11(9.5%)
2. Draught proofing of windows and doors.	80 (69%)	24 (20.7%)	12(10.3%)
3. Replacing windows with double-glazed replicas	59 (50.9%)	24 (20.7%)	33(28.4%)
4. Thick insulated curtains for doors and windows	59 (50.9%)	22 (19%)	35 (30.2%)
5. Installing secondary glazing	56 (48.3%)	39 (33.6%)	21 (18.1%)
6. Installing photovoltaic slates on the roof	50 (43.1%)	25 (21.6%)	41 (35.3%)
7. Installing wood burners in the fireplaces	48 (41.4%)	26 (22.4%)	42 (36.2%)
8. Installing ventilation terminals on ceilings	45 (38.8%)	35 (30.2%)	36 (31%)
9. Installing solar photovoltaic panel on the roof	41 (35.3%)	20 (17.2%)	55 (47.4%)
10. Installing external shutters on the windows	38 (32.8%)	28 (24.1%)	50 (43.1%)
11. Applying insulation panels to interior of external walls	35 (30.2%)	30 (25.9%)	51 (44.0%)
12. Installing solar water heating panel on the roof	31 (26.7%)	24 (20.7%)	61 (52%)
13. Installing modern radiators and gas boiler	30 (25.9%)	19 (16.4%)	67 (57.8%)
14. Insulating floor with new flooring at the top	27 (23.3%)	21 (18.1%)	68 (58.6%)
15. Applying insulation panels to exterior façade	20 (17.2%)	22 (19%)	74 (63.8%)

3.2. Simulation results

The building "as is" was modelled over one year using the Bristol EWY (Example Weather Year) weather data file and a simulation time step of 10-min. This gave an annual heat demand of 46.00 MWh, compared to the 43.51 MWh recorded over one year at the real building. Giving an error of 5.4% and proving the model to be valid. The building was also simulated for each of the energy saving measures applied independently, and if all compatible measures deemed by the survey to be acceptable had been completed (scenario 1), and also if all compatible measures had been completed (scenario 2). The list of measures in each scenario is provided in the Appendix and the results are shown in Table 2. The per m^2 of floor area annual heating demand for scenario 1 (89 kWh/m^2) is below the average energy consumption of non-domestic building stock in the UK (127 kWh/m^2 [47]) and represents an 51% reduction from the "as is" case. Therefore, such a retrofit, whilst still a long way from true low energy standards such as Passivhaus, can be considered as offering considerable savings. On the other hand, scenario 2 gives only a 20% reduction.

Table 2
Results for the two scenarios. The "as is" building is assumed to have heating provided by electrical fan heaters in each room. Energy is in terms of final, not primary energy and is per annum.

Categories	Building "as is" (per m^2 in brackets)	All measures (per m^2 in brackets)	Only acceptable measures (per m^2 in brackets)
Total Energy (MWh)	90.12 (0.32)	71.17 (0.25)	88.52 (0.32)
Energy, heating demand (MWh)	46.00 (0.16)	22.69 (0.08)	36.94 (0.13)
Total carbon emission (tCO$_2$)	46.77 (0.17)	25.69 (0.09)	27.17 (0.10)

3.3. Correlation results

Table 3 shows the savings given by the simulation from implementing each measure independently. In carbon terms the greatest impact is achieved by replacing the heating system, then insulating the

Table 3

Measures ranked in order of carbon savings. The reduction is based on subtracting the carbon emission of the building with the measure applied from the "as is" base case. Ventilation terminals on ceilings were modelled as representing the ducts of a mechanical ventilation system with heat recovery. This only makes sense in a near airtight building, so at the same time total infiltration (windows, doors and fabric) was reduced to a minimum value of 0.03 ac/h typical of a Passivhaus dwelling at normal atmospheric pressure. CO_2 emissions were as output by IES and based on [48].

Alteration	Reduction in CO_2 ($kgCO_2$) per annum
1. Wood Burners in fireplaces as local heating system for rooms (electrical heating in corridors)	18900
2. Central heating system for whole building with natural gas (modern radiators)	12816
3. Applying insulation panels to exterior façade	7948
4. Applying insulation panels to interior of external walls	7444
5. Installing ventilation terminals on ceilings	6797
6. Installing secondary glazing	4109
7. Installing double glazing	3733
8. Draught proofing of windows and doors	1885
9. Thick insulated curtains for doors and windows	1473
10. Installing solar hot water panel on the roof	1173
11. Insulating floor with new flooring at the top	1167
12. Installing external shutters on the windows	1033
13. Installing solar photovoltaic panel on the roof	674
14. Installing photovoltaic slates on the roof	285
15. Baseline/Draught proofing of ground floor	0

Table 4

Ranking of measures in order of visual compatibility, energy saving and carbon emission.

Alterations	Public Rank, P_r	Carbon saving Rank, C_r
Draught proofing of ground floor	1	15
Draught proofing of windows and doors.	2	8
Replacing windows with double-glazed replicas	3	7
Thick insulated curtains for doors and windows	4	8
Installing secondary glazing	5	6
Installing photovoltaic slates on the roof	6	14
Installing wood burners in the fireplaces	7	1
Installing ventilation terminals on ceilings	8	5
Installing solar photovoltaic panel on the roof	9	13
Installing external shutters on the windows	10	12
Applying insulation panels to interior of external walls	11	4
Installing solar hot water panel on the roof	12	10
Installing modern radiators and gas boiler	13	2
Insulating floor with new flooring at the top	14	11
Applying insulation panels to exterior façade	15	3

walls. Due to the floor construction, draught proofing of the ground floor did not affect the overall energy consumption of the building, however this would not be true for all constructions. The rankings produced by the survey and the simulations are compared in Table 4.

To discover if there is any correlation between the two rankings we use Kendall's tau test. The result, a correlation coefficient of −0.257, with a p-value was 0.181, is not significant at either the 0.01 or 0.05 levels. Therefore, we can conclude that there is no correlation between the ranking given by the public and carbon savings of a measure.

The lack of a correlation is also clear if we present the results visually (Fig. 4). It is evident that there is no simple relationship, and it would be wrong to assume that there is a tendency for greater savings

implying greater unacceptability.

Fig. 4 also shows the Pareto front [6]. This line represents the points where a better solution cannot be found without it being worse under at least one ranking. A solution located a considerable distance from the line is seen as less sensible than other solutions, as either the energy savings can be improved by choosing a different solution without decreasing public acceptance, or a different solution can be found that increases acceptance, without reducing energy savings.

Given the Pareto front, we can measure how far any measure is from the front. This is the minimum distance, D, between the point that represents the measure and the curve (Table 5). Plotting these distances, gives Fig. 5.

We can roughly split the solutions into three groups by eye: *logical* (in that they are not dominated, and hence solutions that are simultaneously better to both parties do not exist), *neutral* (in that they might well be worth considering by both those interested in heritage and those interested in the climate change mitigation agenda), and *illogical* (in that better, less controversial to both parties, solutions can be found). An alternative to forming these groups by eye, is to calculate the first derivative of the distance with respect to Pareto rank, r, i.e. dD/dr. This shows (Fig. 5) two major peaks, splitting the data naturally into the logical, neutral and illogical categories.

For example, installing wood burners is identified as *logical*, secondary glazing as neutral and a solar hot water panel as illogical. This is not to suggest that within the context of the retrofit that the rejection of a logical measure would not be sensible after further consideration of heritage value or cost, just that it would be highly logical to ensure it was given further analysis. By splitting the space in this way, rather than using a classification based on solely carbon savings or solely character preservation, or one that tries to artificially blend the two into a single metric, solutions that are ranked highly under either ranking are preserved for future debate within any protect team, whilst dominated solutions, that have alternatives which are better to both parties are rejected, thereby simplifying the discussion.

4. Discussion

Not detecting a direct negative relationship between the conservation perceptions of the public and energy efficiency objectives can be regarded as a favourable outcome for balancing conservation and energy efficiency. It means that there is no need for radical trade-offs, and the conservation perception and energy efficiency targets have no absolute conflicts. However, it also shows there is no natural synergy between savings and acceptability.

This means the question of how to find a balance is still there. The compatibility of energy retrofit measures with historic identities of buildings, as perceived by expert opinion seems to be currently the main determinant of acceptability [1,3,49] and to evaluate this compatibility, conservation principles are regarded as the primary source [19]. The reverse, that the compatibility of conservation and energy saving should be judged on the potential for energy or carbon savings, is controversial, but with the dangers of anthropogenic climate change becoming more commonly understood, less so. By using a Pareto analysis, we have stayed agnostic to which should take precedent, which has allowed us to remove solutions from the debate that are unlikely to appeal to either party, thereby reducing the options and allowing effort to be placed on exploring a smaller number of options.

This new approach has suggested a series of interesting possible future studies: (i) the use of photo-editing software to embed the images of the measures onto photographs of the building in question; (ii) looking not just at the energy or carbon saved by a measure, but including the cost effectiveness of the measure; and (iii) repeating the work, but using experts, not the public as the participants.
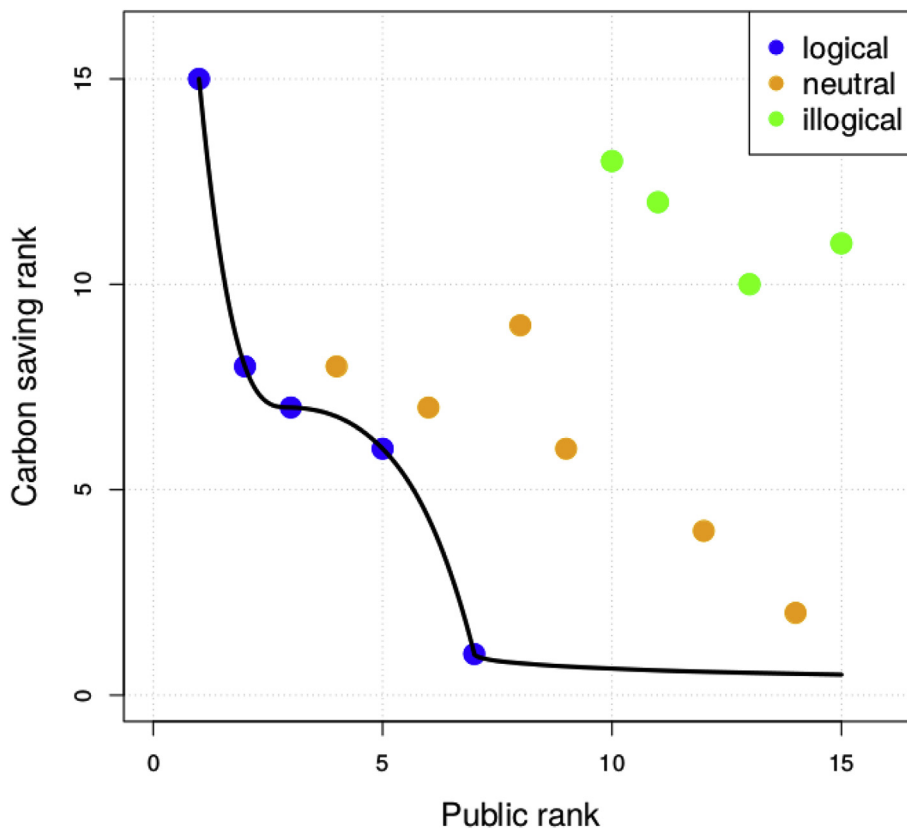
Fig. 4. Scatter plot of carbon saving rank w.r.t. the public's ranking. The Pareto front is shown by the black curve. The red arrow indicates how distance, D, is measured in Table 5, and the shaded area shows the clearly dominated solutions. Individual measures can be identified by referring to the public rankings given in Table 1. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 5
Measures ranked by distance from the energy Pareto front. Measures are shaded green (logical), blue (neutral), orange (illogical) under the Pareto analysis applied.

Rank (by distance from the front)	Public ranking	Measure
1	1	Draught proofing of ground floor
2	7	Installing wood burners in the fireplaces
3	3	Draught proofing of windows and doors
4	3	Replacing windows with double-glazed replicas
5	13	Installing modern radiators and gas boiler
6	4	Thick insulated curtains for doors and windows
7	15	Applying insulation panels to exterior façade
8	5	Installing secondary glazing
9	11	Applying insulation panels to interior of external walls
10	8	Installing ventilation terminals on ceiling
11	6	Installing photovoltaic slates on the roof
12	9	Installing photovoltaic panel on roof
13	10	Installing external shutters on the windows
14	12	Installing solar hot water panel on the roof
15	14	Insulating floor with new flooring at the top

5. Summary and conclusion

Given the urgent need to reduce carbon emissions from the existing building stock, it is inevitable that pressure will grow to find solutions for the historic stock. This suggests the need to create frameworks that will allow conflicts between conservation perception and energy reduction to be discussed and compromises reached. This study compared the ranking of 15 energy saving measures as given by the public, with that given by an energy analysis of the property. This was done in a novel way by presenting participants with photographs of the property

and of the measures applied to different buildings, thereby creating a practical method that can be used by those with responsibility for retrofitting particular buildings, or retrofit policy within local or national government. No significant correlation was found between the two rankings. Importantly, this result contradicts Héberlé and Burgholzer [16] who found a negative relationship between energy savings and impact on historic character, when using experts rather than the public as the judges of character. Hence the conclusion from our work is not that expert opinion should be rejected, as only they are likely to understand the deeper context of any building and its true value to
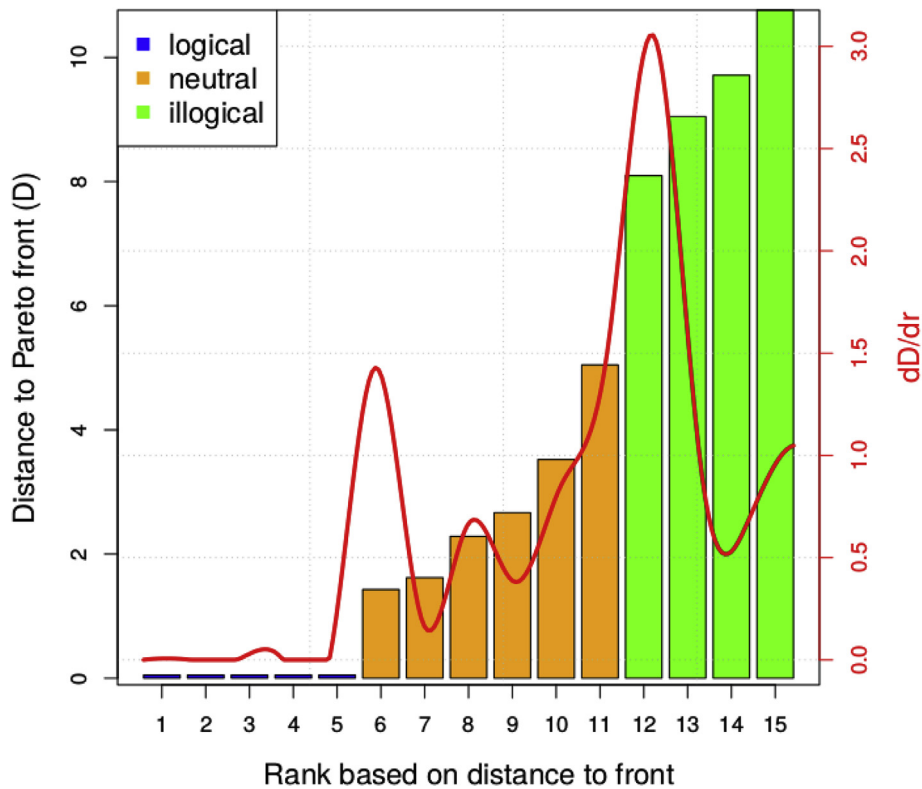
Fig. 5. Bars, distance, D, of each solution from the Pareto front; and line, dD/dr clearly identifying the boundaries between the three categories of measure. Individual measures can be identified by referring to the rankings given in Table 5.

society, but that public opinion should be included in any analysis. The method developed here, would seem to be a highly effective way of doing this.

This paper develops a new presentational theory that places equal weight on energy conservation and historic conservation perception, and remains agnostic to both, by not attempting to find a single quantitative function that merges both views—a task which is unlikely to prove successful. By splitting the resultant space into solutions that are logical, neutral or illogical, based on the first derivative of the distance to the Pareto front, the discussion space is reduced in size,

allowing for a concentration on a small range of options, but without losing options from the discussion that represent highly valued measures from both sides of the debate.

Appendix

Building details

- The building is located in Bath at 51.38°N, 2.37°W.
- The floor area is 280 m^2 with ceiling heights of 2.80 m (basement, second and third floors), and 3.20 m (ground and first floors).
- The museum is open to the public 13:00–17:00 weekdays and 11:00–17:00 weekends with an assumed occupant density of 2 people per room. Outside of these hours but between 09:00–18:00, the museum is assumed to be occupied by staff at 0.2 people per room.
- Lighting was set to 120 W per room, i.e. assuming old fittings and non-LED technology.
- Heating was electric (100% efficient) set to 19 °C and a nominal hot water (DHW) consumption of 0.1 l/hr/person.
- Windows and doors: opening at 23 °C during occupied hours for cooling.
- Adjoining buildings either side of the party walls were controlled to 19 °C continuously.
- Carbon intensities of fuels used: electricity – 0.519 kgCO$_2$/kWh, natural gas – 0.216 kgCO$_2$/kWh, wood – 0.031 kgCO$_2$/kWh.

Base case construction details

- External walls – 400 m Limestone, 25 mm plaster, 2.0154 W/m^{2}K.
- Party walls – 25 mm plaster, 400 mm limestone, 25 mm plaster, 1.5487 W/m^{2}K.
- Internal walls – 13 mm plaster, 360 mm brick, 13 mm plaster, 1.1080 W/m^{2}K.
- Glazing – 4 mm clear float, 5.4891 W/m^{2}K.
- Doors – 50 mm oak, 2.3086 W/m^{2}K.
- Ground floor – 750 mm clay, 250 mm brickwork (outer leaf), 100 mm concrete, 50 mm screed, 10 mm carpet, 0.7059 W/m^{2}K.
- Internal floors – 13 mm plaster, 250 mm cavity, 25 mm oak flooring, 10 mm carpet, 1.2585 W/m^{2}K.

- Roof – 5 mm slate tiles, 5 mm roofing felt, 250 mm cavity, 25 mm plaster, 2.5074 W/m²K
- Infiltration set to 0.166 l/sm² for the external facade and 1 l/(smPa$^{0.6}$) for crack flow around windows and doors (calculated from values in Ref. [50]).
- Background ventilation is provided at 3 l/s/person from external air.

Additional intervention details

- Due to the inbuilt assumptions with dynamic modelling software, draught proofing of floors has no affect and was not simulated. Although in practice this will likely improve occupant comfort through the reduction of draughts.
- Draught proofed windows and doors – crack flow infiltration rate reduced to 0.14 l/(smPa$^{0.6}$) (calculated from values in Ref. [50])
- Secondary glazing – 4 mm secondary glazing installed with a 20 mm air gap from the existing frame, crack flow infiltration rate reduced to 0.044 l/(smPa$^{0.6}$) (calculated from values in Ref. [50]), U-value reduced to 2.7827 W/m²K.
- Double glazing – U-value set as 1.6 W/m²K for a 6-12-6 mm argon filled cavity, hardwood frame and low-ε coated glass, infiltration set to 0.14 l/(smPa$^{0.6}$).
- External shutters with R = 2.5 m²K/W [51], closed outside occupied hours.
- Insulated curtains with R = 2.5 m²K/W [51], closed outside occupied hours.
- Photovoltaic roof tiles – 18% efficient, 3.4 m², 0.37%/K temperature degradation from 25 °C (based on Tesla roof tiles).
- Photovoltaic panels – 15.64% efficient, 9.2 m², 0.44%/K temperature degradation from 25 °C (based on Samsung Black series 255 W).
- Solar thermal hot water – 2.18 m² flat collector, 76% conversion efficiency with a 40% heat exchanger effectiveness and a 1000l storage tank.
- Wood burners – located in rooms, 85% efficient, with electric heating in corridors and electric DHW.
- MVHR ceiling terminals – total building infiltration reduced to 0.03 ac/h and 3 l/s/person background ventilation now supplied via an 85% efficient (sensible) heat recovery unit.
- Wall insulation (internal) – 50 mm EPS added between limestone and plaster, new U-value 0.4006 W/m²K (0.3780 W/m²K for party walls).
- Wall insulation (external) – 5 mm stucco, 20 mm fibreboard, 100 mm fibre insulation board added to exterior, new U-value 0.3163 W/m²K.
- Gas boiler and radiators – assumed condensing boiler 90% efficient, covering all areas and DHW.
- Insulating internal floors – 50 mm fibre insulation board added beneath floorboards, new U-value 0.5109 W/m²K.
- U-value for both internal and external insulation 0.1937 W/m²K.
- Solar thermal and photovoltaics were assumed to face south at 30° inclination even though road side façade is north facing in order to represent maximum generation potential.

Scenarios

As not all measures are compatible, for example it is unlikely secondary glazing would be fitted at the same time as double glazing, hence the two scenarios contain a slightly reduce set of measures. Where non-compatibility was found, the measure with the greatest carbon saving was used.

Scenario 1 (acceptable measures)	Additional measures added under Scenario 2 (all measures)
Draught proofed floors	External shutters on windows
Draught proofing windows and doors	Interior wall insulation
Insulated curtains on windows	Solar thermal DHW panel
Secondary glazing	Condensing gas boiler + radiators
PV tiles	Insulating the floors
Wood burners	External wall insulation

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